
STUDY OF OPTICAL TECHNIQUES FOR THE AMES UNITARY WIND TUNNELS PART 1. SCHLIEREN

George Lee

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Summary

Alignment procedures and conceptual designs for the rapid alignment of the Ames Unitary Wind Tunnel schlieren systems have been devised. The schlieren systems can be aligned by translating the light source, the mirrors, and the knife-edge equal distances. One design for rapid alignment consists of a manual pin locking scheme. The other is a motorized electronic position scheme.

A study of two optical concepts which can be used with the schlieren system was made. These are the "point diffraction interferometers" and the "focus schlieren." Effects of vibrations were studied.

Ames Unitary Schlieren Systems

Introduction:

The Ames 9x7 Foot Supersonic Wind Tunnel schlieren system is currently being modernized to provide better data and higher efficiency. Major renovations include:

1. replacement of the existing high power mercury arc lamps with high efficiency xenon flash lamps;
2. replacement of the condenser lens with anti-reflection coated lens to increase the transmissivity;
3. modify the light source housing for several different sources for various forms of visualization; and
4. provide capabilities for image processing.

At the same time, easier, more accurate, and faster ways to align the schlieren systems must be considered. Past alignment was a tedious and slow process, sometimes taking many hours. The reasons were a lack of alignment procedures, worn out parts, and

ambiguous alignment markers. To better understand the problems, a brief description of the Unitary schlieren systems shall be given.

The Unitary schlierens are typical Toepler off-axis or "Z" shaped configurations, see figure 1a. Some pertinent data and the original design drawings for the 9x7 supersonic wind tunnel schlieren system is listed in Table 1. Detailed description of Toepler systems can be found in Holder and North^{1,2}, Schardin³, and Merzkirch⁴. The 9x7 schlieren, figure 2a, is designed to cover the two test section windows. The 11x11 schlieren, figure 2b, covers the three sets of rectangular test section windows. The Unitary schlieren consists of a light source assembly, two 48" diameter mirrors, and the knife-edge/camera/video assembly, all which are mounted on carts. The carts roll parallel to the test section to cover the windows. Currently, the carts are pushed to alignment marks painted or scribed on the floor. The 9x7 markers for the mirrors seems to correspond to the two test section window. But there are extra sets or marks for the light source and knife-edge carts. Perhaps they are for setting different "Z" configuration. The 11x11 has 15 evenly spaced marks of 6" for the mirrors and light source. There are no marks for the knife-edge. In all cases, the painted markers are quite worn which makes for difficult alignment. No documentation was found on how to align the schlieren system or how to use the markers. These factors contributed to the time required to align the systems. It was also found that the mirrors have been tilted about the horizontal and vertical axis, (which will change the "Z" configuration and the location of the system with respect to the alignment markers). As the systems was designed, there is no need to tilt the mirrors about the horizontal axis once the beams have been aligned horizontally. The system was designed for the light source, the center of the mirrors, and the knife-edge to be at the same height of the test section center line. It is surmised that the capability to tilt the mirrors horizontally is for the initial leveling of the beams only. The mirrors should not be adjusted about its horizontal axis thereafter. The mirrors are also designed to rotate about its vertical axes to align the system to the desired "Z" configuration. Usually, the "Z" is aligned for equal angles, $A_1=A_2$ (see a) to reduce comma. According to Holder and North, the angle A should be less than 10 degrees to minimize the astigmatism. The 9x7 schlieren system is set at about 6.5 degrees based on measurement of the tracks and mirror focal length. Therefore, once the angle A have been initially aligned, there is no need to rotate the mirrors

about the vertical axes. Based on the above knowledge, the alignment of the Unitary schlieren systems should consist of lateral movements of the light source, two mirrors and the knife-edge equal distances. (This will maintain the "Z" configuration.) There may be a need to compensate for small changes in the height of the floor as the system is moved. This probably could be done at the knife-edge. Now that it is known that the alignment should consist of equal movement of the system, two schemes are proposed for the rapid and accurate alignment of the 9x7 and 11x11 foot systems.

Manual Alignment Scheme

A simple and very accurate scheme for aligning the schlieren to cover the 9x7 test section would consist of taper pins to position the four components of the schlieren system. This conceptual design would require welding a steel bracket to the bottom of each of the four carts containing the light source, mirrors, and knife-edge. After alignment to the desired positions, holes will be matched, drilled between the brackets and the steel tracks in the floor. Taper pins will be used to lock the carts to the floor. This simple scheme can be used to cover the two window frames in the 9x7 test section, figure 3a. The 48 inch diameter schlieren beam is large enough to overlap the 28 inch diameter viewing port as it is rotated to any position, figure 3b. For the four configurations shown in figure 4a, the viewing ports and the mirrors can be lined up so that its centers are on the same axis, figure 4b. The beam is now concentric with the viewing ports to further minimize astigmatism. This refined scheme would require four more sets of holes.

This taper pin scheme could also be used in the 11x11 TWT. The window in this tunnel is essentially rectangular and is about 50 inches high by 130 inches wide. To cover this area, a number of pin positions would be required. The current painted marker systems uses 15 markers spaced 6 inches apart which would cover most of the width of the window, figure 4c.

Motorized Alignment Scheme

The following motorized scheme is proposed as an alternate to the taper pin scheme. It has the advantage of being able to put the schlieren beam at any part of the test section. Its main use would be in the 11x11 TWT. The motorized system would consist of a motor to drive a ball screw to move the cart. An optical encoder with a

programmable motion controller can be used to accurately position the system. As an example, a ball screw with a screw pitch of 10 and a rotary optical encoder of 1000 line counts per revolution gives a system resolution of 0.0001 inches. This is much more resolution than is needed since defraction, backlash in the screw, and the subjectiveness in obtaining a uniform image field is more than this. A sketch of the motorized design is shown in figure 5. An estimate of costs and some typical parts are given in Table 2.

Alignment Procedure

This alignment procedure is for the initial alignment of the 9x7 schlieren system or after the mirrors have been tilted. The procedure follows basically the one given by Holder and North. The purpose of the procedure is to focus the light source so that the collimated beam from the first mirror passes perpendicularly through the test section windows to the second mirror which captures the beam and focuses it at the knife-edge plane onto the image plane.

1. Remove the window frames from the test section. Locate the centers of the mirrors and window holes with cross hairs. Line up each mirror with the holes with a transmit or with the laser/beam splitter auto collimating scheme shown in figure 6. Move the mirrors until the beam auto collimates and goes through the centers of the mirrors and holes. The next step is to place the light source (slit) at the focal point of the first mirror.
2. Move the light source cart until it is approximately at the focal point of the first mirror. The focal distance is 256 inches.
3. Turn on the light and rotate the first mirror so that the collimated beam goes through the center of the test section holes and fill the second mirror. (This would require moving the second mirror.)
4. Place a board against the inside surface of the test section. Attach a flat mirror against the board to reflect the beam back to the light source. Adjust the light source until the reflected image of the light source superimposes itself on the light source. The light source is now located at the focal

point of the first mirror.

5. Rotate the second mirror and use the auto collimated laser beam to set the angles A_1 , equals A_2 to form the "Z" configuration, figure 1a. Place the knife-edge in the focal plane of the second mirror. Adjust the knife-edge until the screen darkens as uniformly as possible when the knife-edge is reversed across the image of the light source. The 9x7 system has a lens which focuses the image on the screen (this is the plane of the film).

Numerical Simulation

The 9 x 7 schlieren was simulated with a numerical optical ray-tracing code called "Opticad." The purpose was to determine (1) errors caused of misalignment, and (2) locations of the beam waist in order to locate the knife-edge. A summary of the simulation will be given. Details of the analysis will be given in a report by Dana Lynch of the Ames Research Center.

- A. For the perfectly aligned "Z" configuration of the 9 x 7 schlieren:
 1. The image of the a point light source is about 0.5 inch x 0.5 inch.
 2. The image of the vertical focus is about 250 microns wide by 1 inch high and it is located 3.5 inches short of the focal length of the mirror. See figure 1b. This is the location of the horizontal knife-edge.
 3. The image of the horizontal focus is 250 microns high by 1 inch wide and is located at 3.1 inches longer than the focal length of the mirror. This locates the knife-edge in the vertical position.
- B. If a mirror is misaligned 0.5 inch parallel to the test section:
 1. The centroid of the image moves about 100 microns parallel to the test section.
 2. The vertical focus is broader by 50%.
- C. If the light source is misaligned by 0.5 inch:

1. The centroid of the image shifts to 0.5 inch.

D. Beam from a line source:

1. Rotation of the line source will reverse the location of the vertical and horizontal foci.

Optical Concepts

Introduction

A survey of optical techniques that could be adapted to the Unitary Wind Tunnels was done by Aerometrics in 1989. The survey covered shadowgraph, schlieren, moire deflectometry, Mach-Zehnder and laser holographic interferometry, particle displacement velocimetry, and light sheet vapor screen. A critique of these techniques and whether they can be easily used with the existing schlieren was given.

During the past five years, two optical techniques were being developed which show promise of being adaptable to schlieren systems and could have application to the Unitary Wind Tunnels. The two optical concepts are the "large-field focusing schlieren⁵" and the "large aperture interferometer⁶"

Focus Schlieren

The large-field focusing schlieren developed by L. Weinstein is a revival of a concept developed nearly 40 years ago. Two separate versions of the focusing schlieren were developed in the 1940's by Kantrowitz and Trimpi⁸, and by Burton⁹. The Kantrowitz scheme shown in figure 7 consists of two high quality lenses, a source grid which provides the multiple light sources and a cutoff grid which acts as multiple knife-edges. The principle of operation of this concept was given by Kantrowitz. It was shown that each source-cutoff combination produces an independent schlieren image, and for a given screen position, only the shadows produced by density gradients at a single plane in the flow superpose exactly. This means that a two-dimensional slice in a three-dimensional flow field can be obtained. One property is that out of focus planes are not seen or affect the image slightly. One limitation of this scheme is a field of

view that is smaller than the lens. Burton's scheme, figure 8, requires only one lens and uses a diffusing glass to get a uniform field of point light sources. It has the advantage that the field of view is larger than the lens diameter. The diffuser does reduce the light levels. Fish and Parnhan¹⁰ describes the focus schlieren in detail and points out its limitations. Among these are low brightness, small field of view, depth of field problems and difficulties of setting up and adjusting the system. According to Weinstein, this paper seems to discourage the use of focus schlierens. A version of the Kantrowitz scheme was used by Buzzard¹¹ to combine laser holography to obtain three-dimensional data. This setup, figure 9a, splits a laser beam into two paths. One path goes to a multiple array of lens which acts as light sources. A second lens collimates the beams from the lens and passes it through the test section to the hologram. The other beam is the reference beam for the hologram. The holographic reconstruction setup, figure 9b, recreates the original wavefront which is focused on an array of knife edges. By moving the image screen, different planes within the test section are brought into focus. A three-dimensional picture can be obtained. The advantage of this method is a single test hologram is used and the reconstruction is done under laboratory conditions. This scheme is still limited to small field of views. A version of the focus schlieren that uses mirrors (most wind tunnel, schlieren systems use mirrors) instead of lens was developed by Rotem¹², et al. Rotem applied this scheme to a color schlieren to try to obtain quantitative results. This system lacks a depth of focus for three-dimensional flow fields. Recently, Weinstein developed a focus schlieren based on Burton's scheme which show improvements in brightness, large field of view and ease of use. Weinstein's system, figure 10, is essentially the same as Burton's except a Fresnel lens replaces the diffuser. This gives images that are over 100 times brighter. Fresnel lens of the order of a meter are available which means that large field of views can be obtained. The method to design and set up this system are given by Weinstein⁵. This newer version of the focus schlieren has applications to the Unitary Wind Tunnels. First, the availability of cheap, large Fresnel lens of one meter diameter would provide the large views required. Second, the test section window quality is no longer a critical factor. Currently, the 11x11 TWT is using lexan windows which probably precludes the use of the existing Toepler schlieren. Experiments in the Ames Fluid Mechanics Laboratory using a focus schlieren show that images can be obtained in a tunnel with lexan windows. One point needs to be checked; for large focus

schlieren systems, the depth of focus is no longer narrow. This may affect its use in the 11x11 TWT to overcome the lexan windows.

Large Aperture Interferometers

During the past few years, Anderson and Milton^{6,7} have developed a relatively simple modification of the classical schlieren to an interferometer. The two changes are replacement of the light source with a laser, and the knife-edge with some other type of spatial filter. If a pin hole is used as the spatial filter, the system becomes a "field absorption" or point diffraction interferometer¹³⁻¹⁶. If an opaque spot is used as the spatial filter, the system becomes a "dark-central-ground" interferometer. Figure 11 shows a "Z" type schlieren converted to an interferometer. As in a schlieren, the light from the source is collimated by the first mirror. The collimated beam goes through the test section. The distorted wave is focused by the second mirror to the spatial filter which produces a reference wave which interferes with the distorted wave to form the interferogram. Anderson showed that the wave fronts from the "pin hole" and "opaque spot" filters are mathematically related and either filter gives the same results. Anderson also demonstrated methods to make both types of filters. To make a dark-central-ground filter, an unexposed photographic plate is placed with the emulsion at the focus of the second mirror. The laser is fired to char an opaque spot and a perfectly aligned filter is made. If the spot is not dark enough, the laser can be fired again. If the laser burns a hole, the absorptance of the plate can be reduced by placing it in a photographic fixer. To make a pin hole filter, the photographic plate is first exposed and developed to produce a transmittance of about 0.06. The plate is again placed at the mirror focus and the laser is used to burn a hole through the emulsion to produce a properly sized, aligned hole surrounded by an absorbing field.

Carr, et al.¹⁷ have used both types of filters in a converted schlieren interferometer to study unsteady compressible flows over oscillating airfoils. A number of ways to make field absorption filters were tried. One that worked well used a blue-line filter instead of a photographic plate. A clear hole was burned through the blue-line filter. This filter gave increased contrast to the interferograms. There are a number of applications for large aperture interferometry in the Unitary Wind Tunnels. The main advantage of interferometry is that it provides quantitative data. For two-dimensional and

axisymmetric flows, interferometry is very useful since the fringe reduction is straightforward. Computers with specialized routines can digitize the images to give density maps. For two-dimensional flows of "infinite fringe" interferograms, the fringes become iso-density contours which makes interpretation and data reduction a simple task. For three dimensional flows, the data reduction is much more complicated and tomographic techniques requires viewing the model from different angles. At this time, the state of the art of tomography probably prohibits its use for production testing. For flow visualization, interferometry has some advantages over schlieren and shadowgraph. It can be more sensitive. Detail flow structures such as boundary layers, wakes, and shock-boundary layer interactions can sometimes be better seen and interpreted by the fringes. Flow visualizations can also be seen in regions where no clear optical path is available, i.e. the model blocks the view. By painting the model with 3M Scotchlite retroreflective paint, interferometry can be used to see these regions. A common case would be the wing body junction region.

Vibration Effects

Vibration of the schlieren system can cause a deterioration of the image, i.e. loss in contrast. It can introduce dark regions into the image in regions of large density gradients. In the worst case, if the image of the source is displaced completely off or on to the opaque side of the knife-edge, the schlieren picture will oscillate between a light and dark image. Methods to estimate deflections are given by Mair¹⁸ for shocks (a strong density gradient) and expansion waves (a weak density gradient). One can use these methods to calculate the loss of sensitivity caused by vibration. At first glance, it would seem that the vibration of the Unitary schlierens would be a problem. The schlieren are mounted on seemingly flexible floors. However, accelerometer measurements by Martens and Lee showed that typical movements of the system were of the order of 0.001 to 0.002 inches. This probably caused some changes in picture contrast, but not a serious problem.

Recommendations

1. Install manual pin alignment design for the 9x7 Foot Supersonic Wind Tunnel.

2. Install motorized alignment design for the 11x11 Foot Transonic Wind Tunnel.
3. Design a focus schlieren system for the 11x11 Foot Transonic Wind Tunnel during the interim period of lexan windows.
4. Develop a "schlieren interferometer" for the Unitary Wind Tunnels.

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TABLE 1

9 x 7 Schlieren Information

Mirrors:

- spherical shape
- 48" aperture
- 256" focal length
- first coated aluminum

Light source:

- Xenon flash lamp (max. rate = 500 pps, typical operation = 30 to 60 pps. Also single pulse operation
- light source slit is adjustable (typical = 0.16")

Knife edge:

- gelatin color bands

Estimated weights:

- mirror and cart = 2500 lbs
- light source cart = 500 lbs
- camera/knife edge cart = 500 lbs

Reference drawings:

- Schlieren system, A10260-D4 to A10260-D74
- Windows, carts, A9750-D1 to A9750-D14
and A9730-C2 to A9730-C8

TABLE 2

Cost Estimate for
Motorized Alignment Hardware
(for one cart)

Part	Approx. Cost
1" dia. ball screw; Raceaway Saginaw Products Saginaw, Michigan (517)7853-1411	
1. leadscrew, part no. R42-1	\$ 234
2. ball nut, part No. R422	\$ 142
3. flange, part No. R-42-3	\$ 26
4. wiper, part no. R42-4	\$ 20
Stepper motor Compumotor, Parker Hannifin Corp. Petaluma, CA 1-800-358-9068	
1. motor, drive, and indexer, part no. SX-106-178	\$2500
Position indicator	
1. Optical encoder, part no. 152-12110000-12005546 Dynamic Research Corp. Wilmington, MA 1-800-323-4143	\$ 225
2. Indicator, part no. 7960 08-00v Veeder Root Simsbury, CT 203-651-2700	\$ 210
Total Cost	<u>\$3357</u>

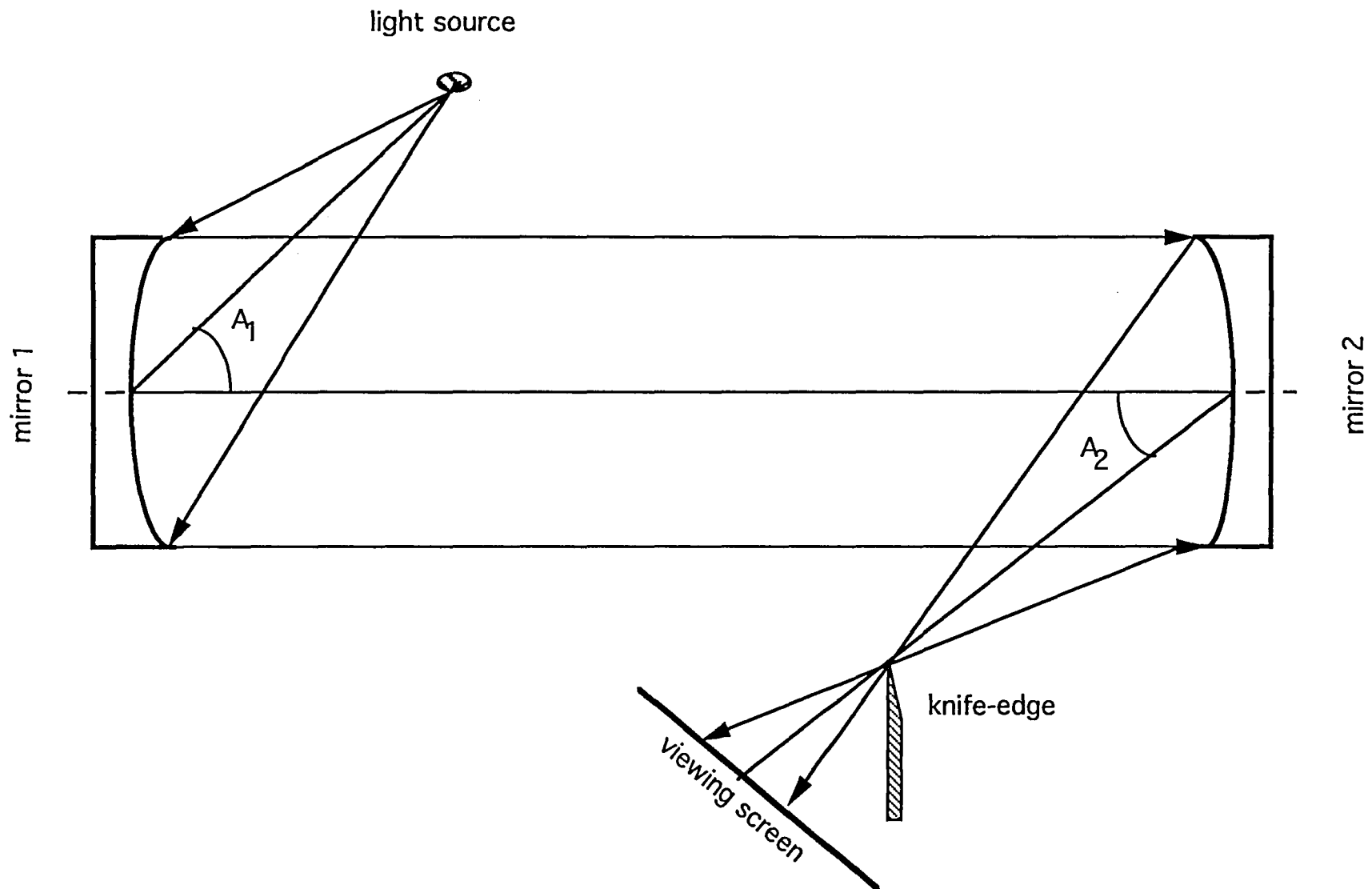


Figure 1a. Off-set Toepler Schlieren System or Z configuration.

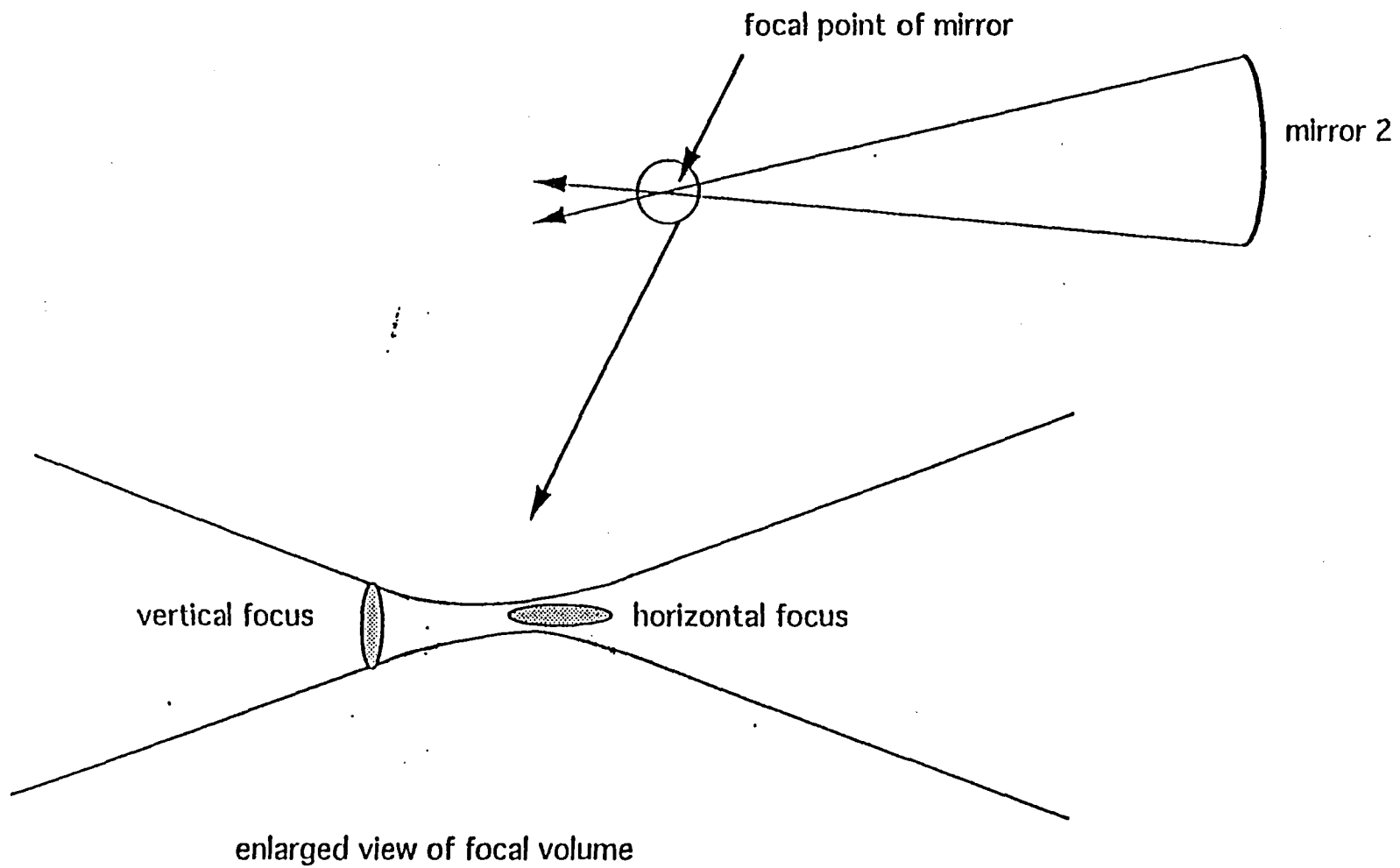


Figure 1 b. Sketch of foci from numerical simulation.

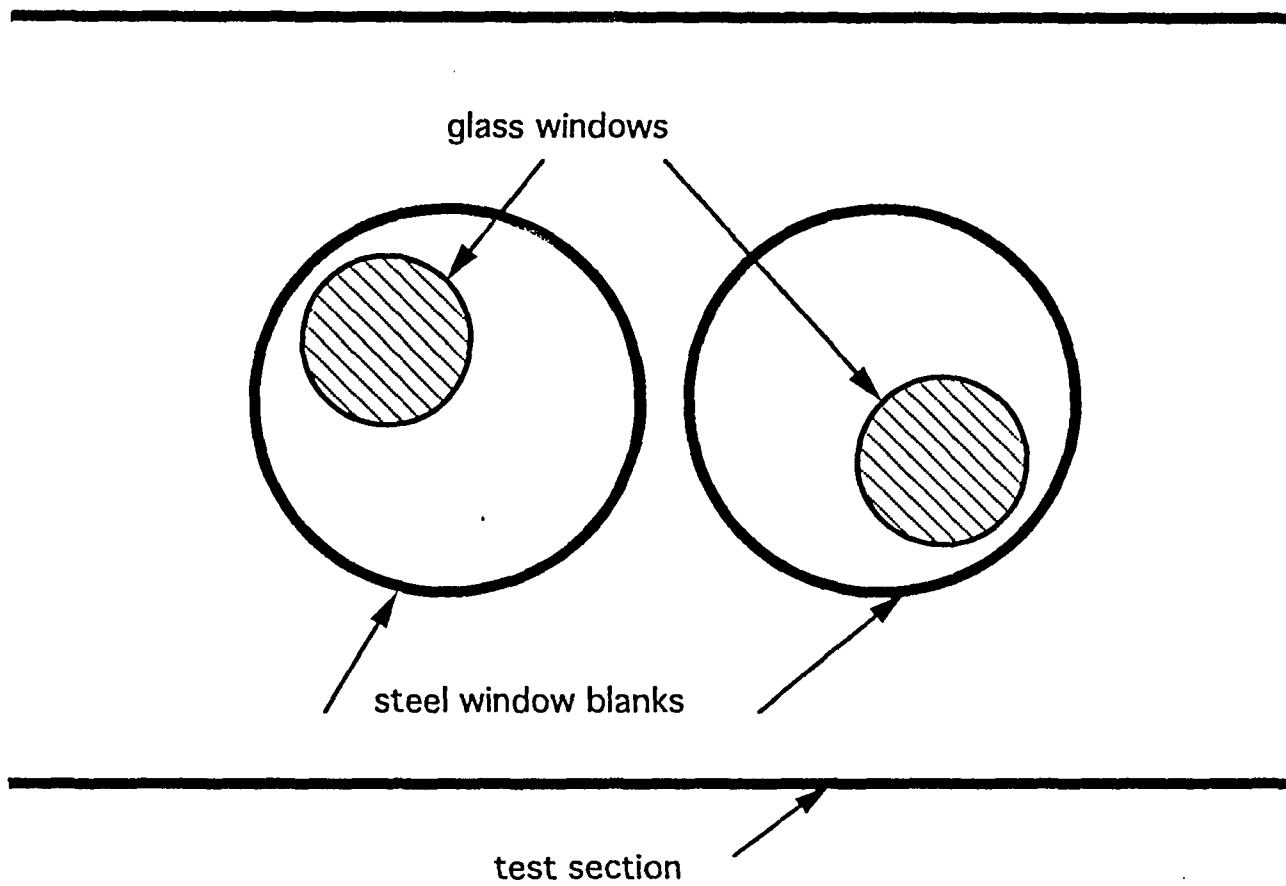


Figure 2a. Window arrangement of 9x7 Foot Supersonic Wind Tunnel.

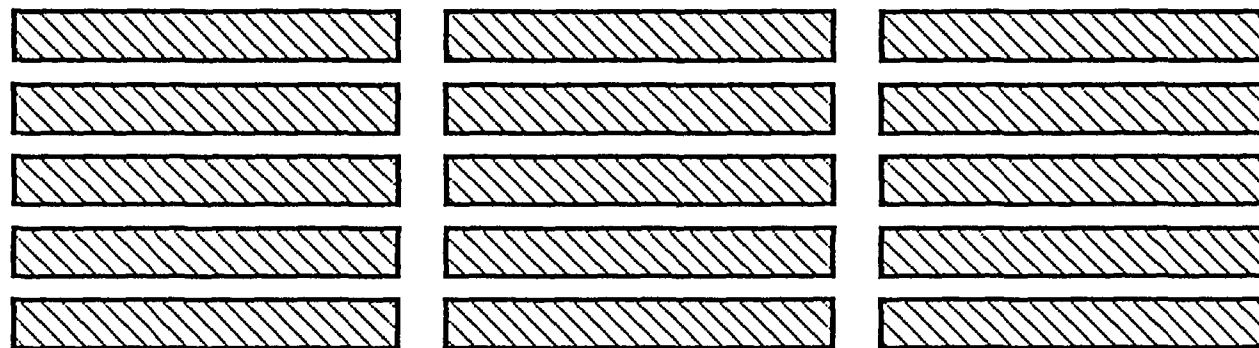


Figure 2b. Window arrangement of 11 x11 Foot Transonic Wind Tunnel.

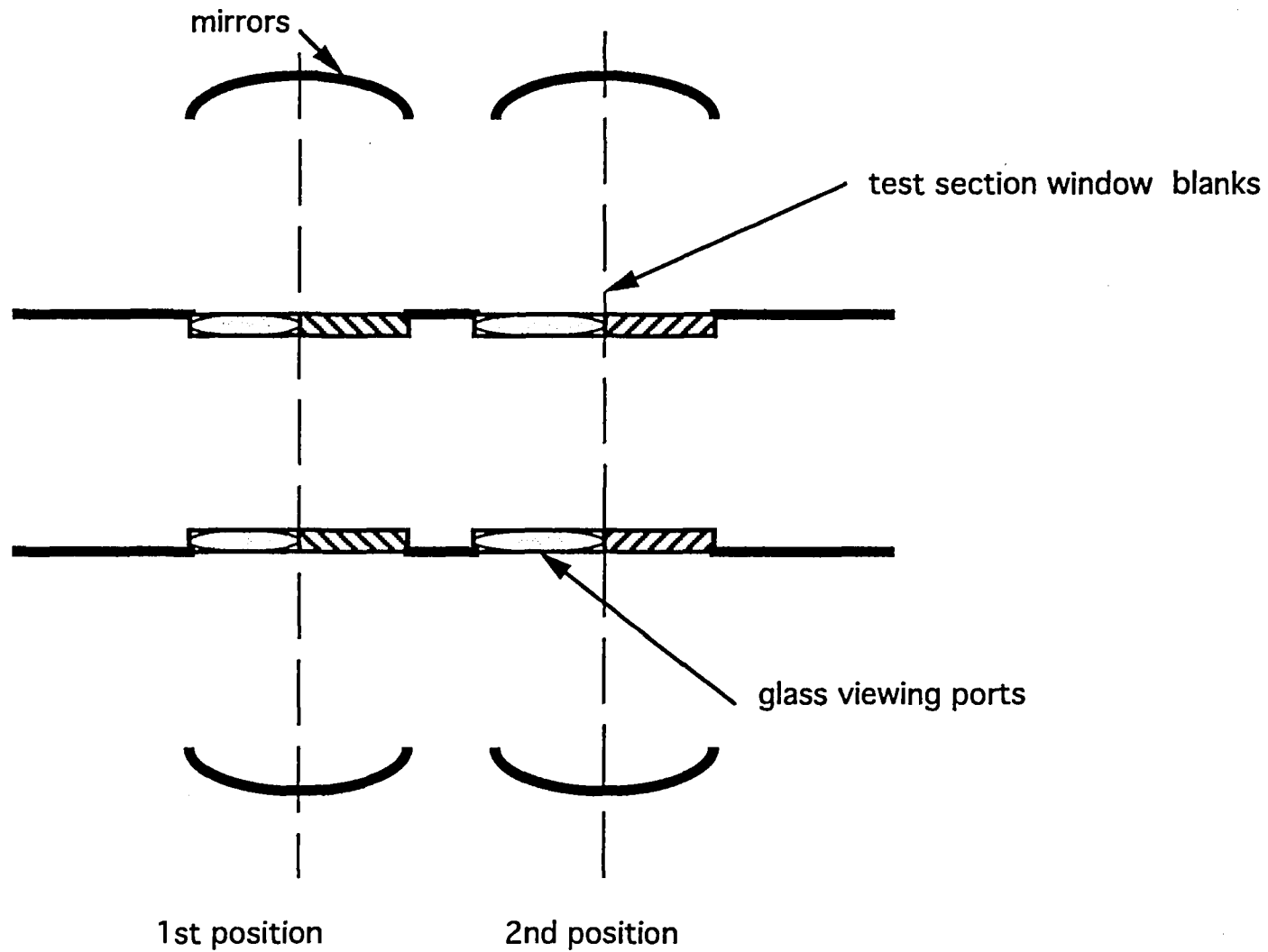


Figure 3a. Schlieren system at positions 1 and 2 of the 9x7 Supersonic Wind Tunnel.

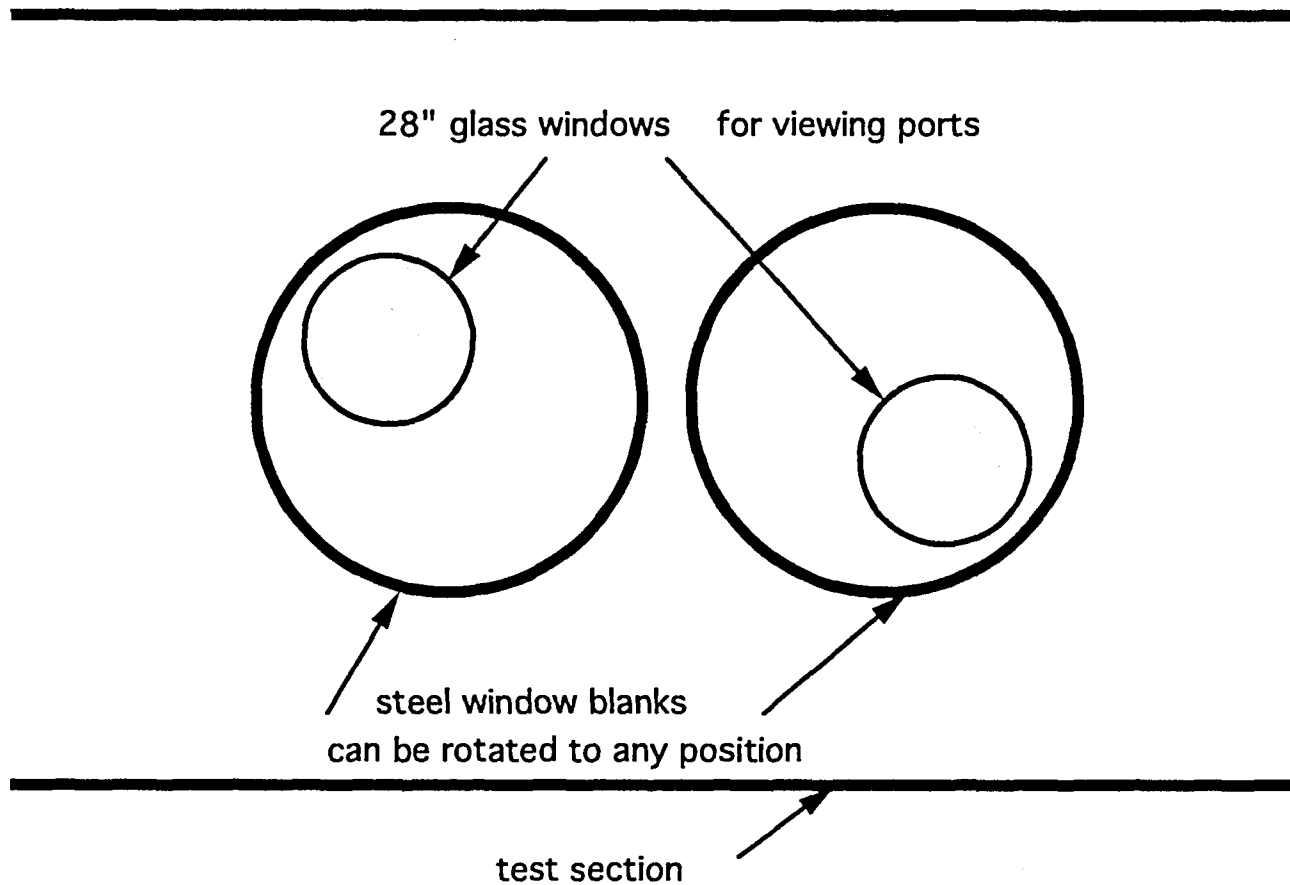
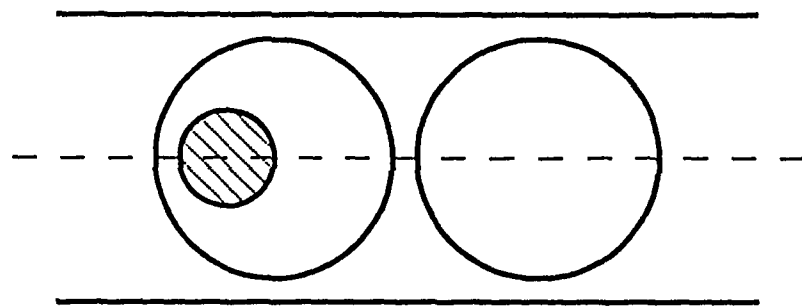
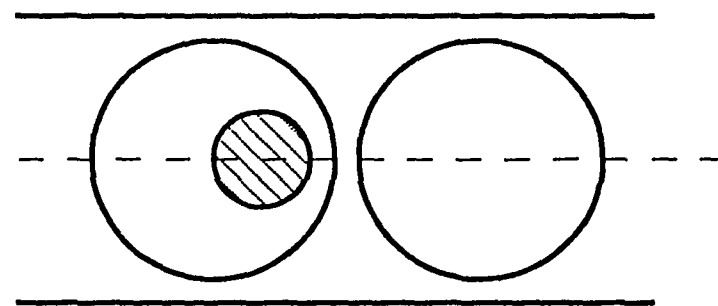


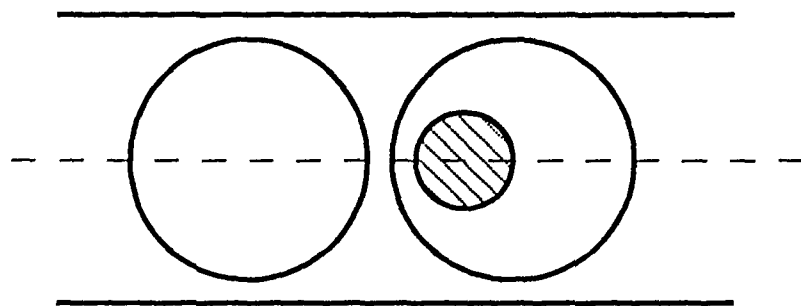
Figure 3 b. Viewing port arrangement of 9x7 Foot Supersonic Wind Tunnel.



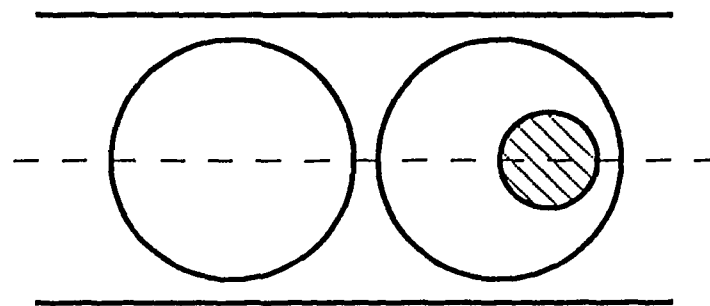
1



2



#3



#4

Figure 4a. 9x7 viewing ports in the four horizontal positions.

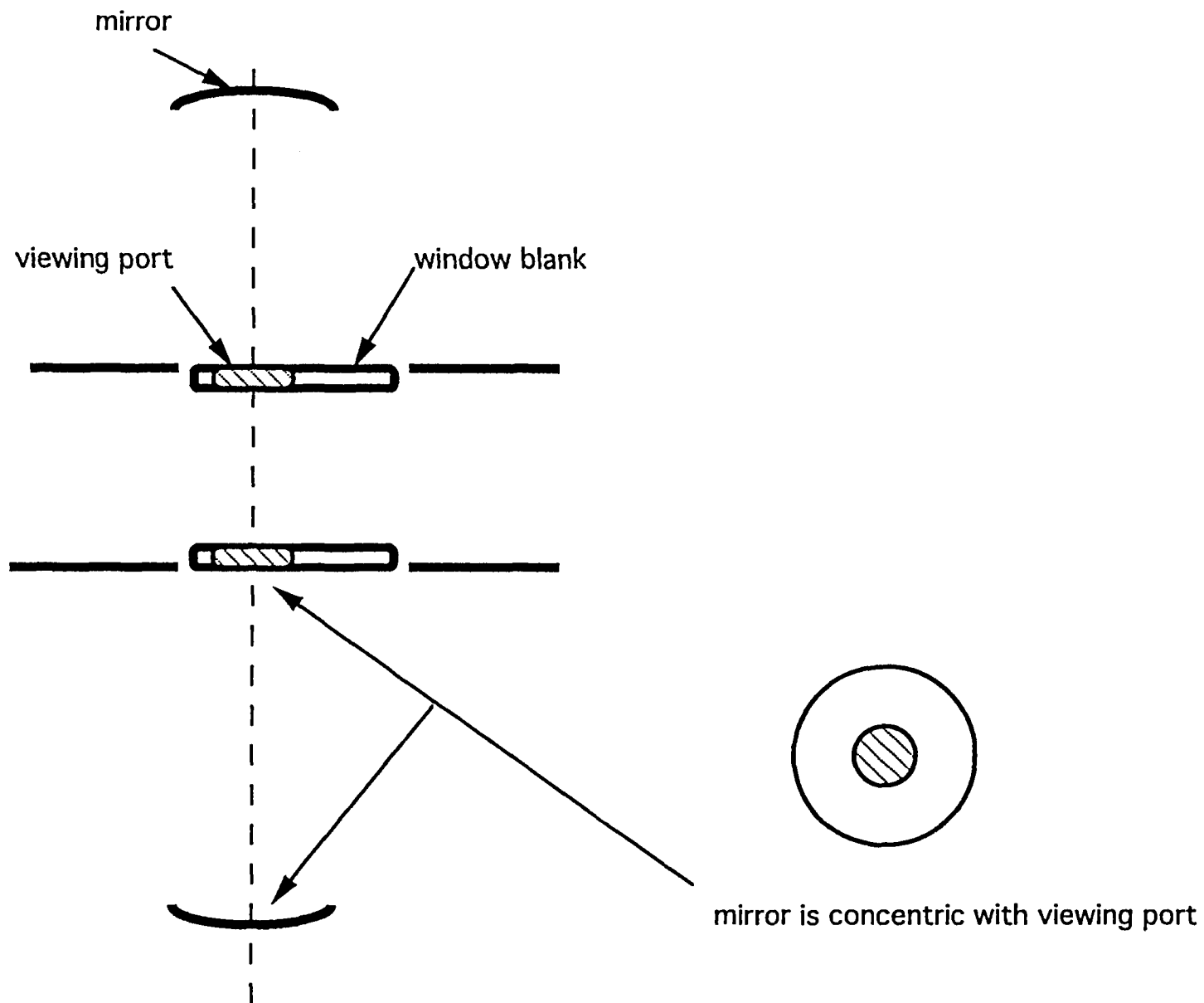


Figure 4b. Mirror aligned concentrically with viewing port in horizontal position.

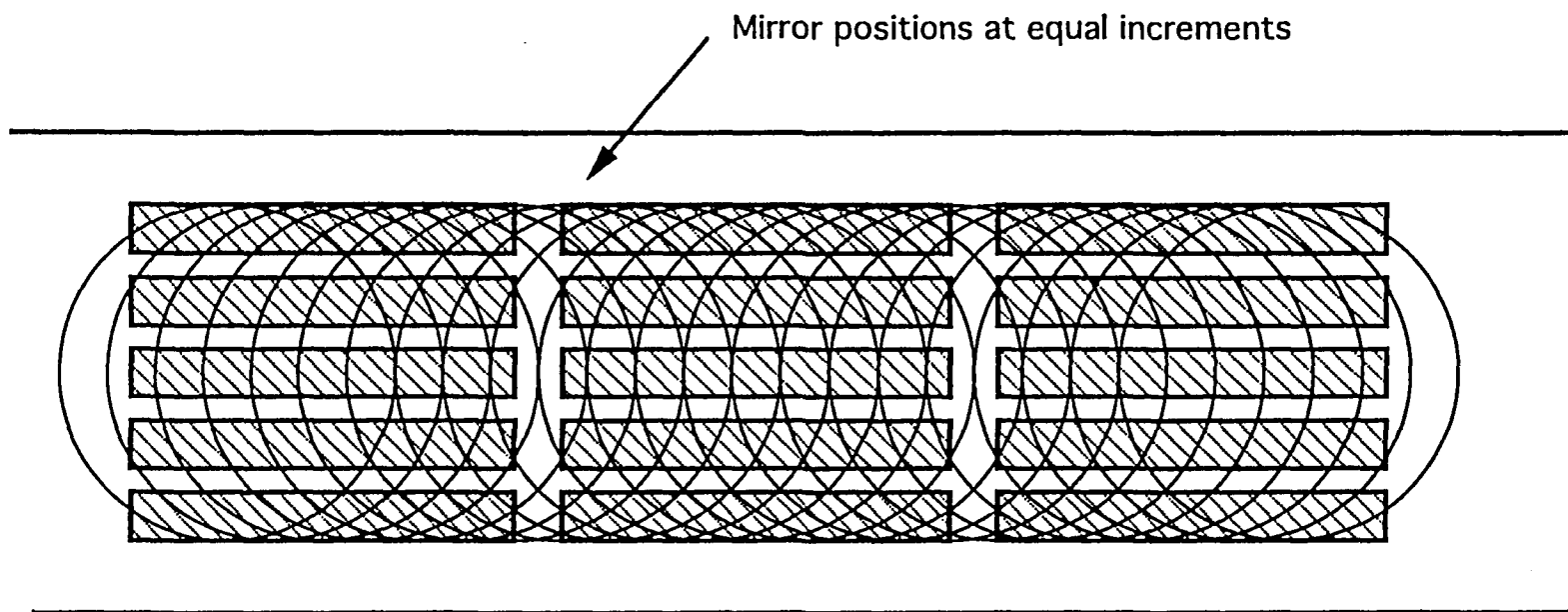


Figure 4c. Mirror arrangement of 11 x11 Foot Transonic Wind Tunnel.

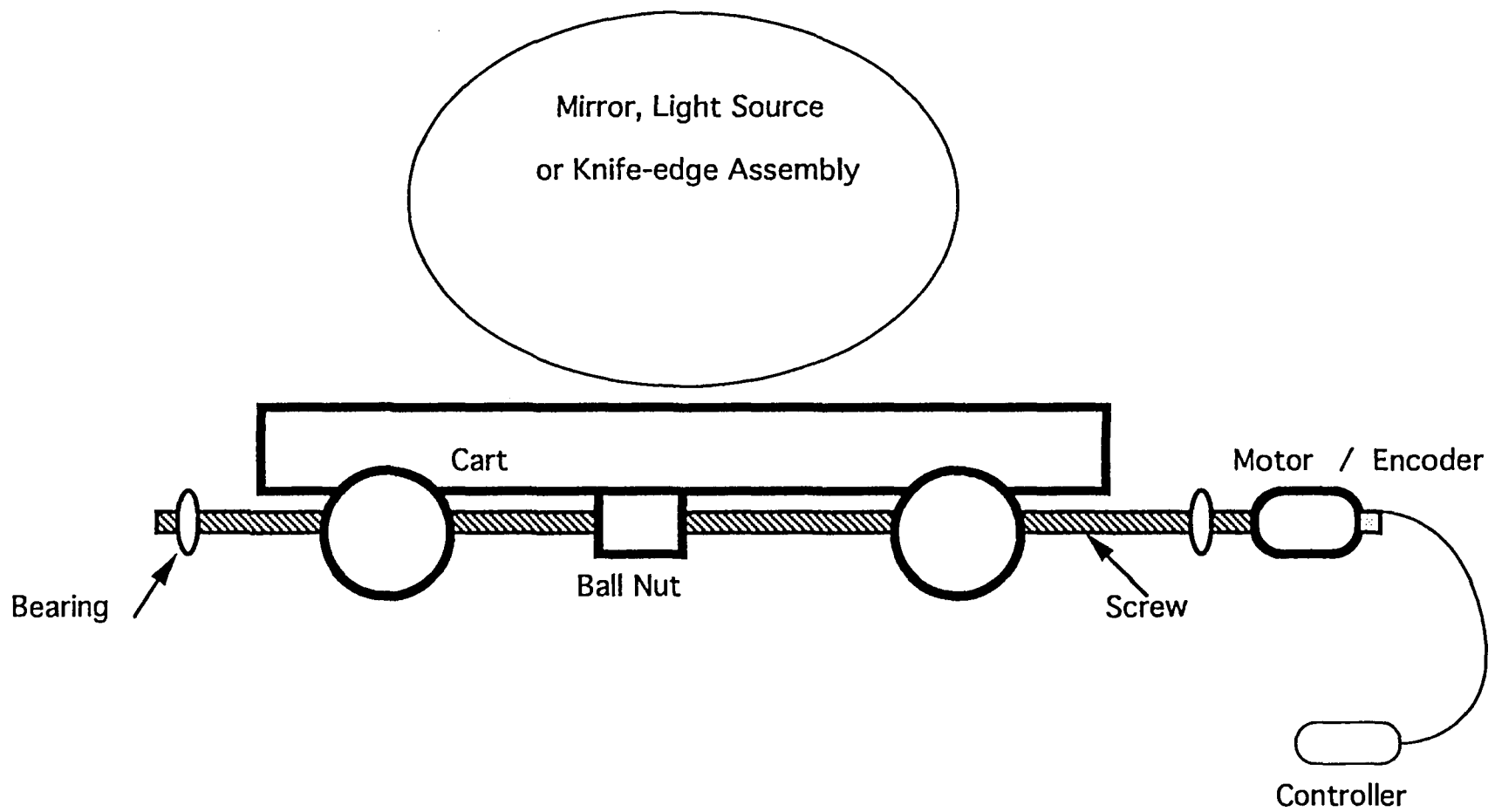


Figure 5. Motorized Alignment System.

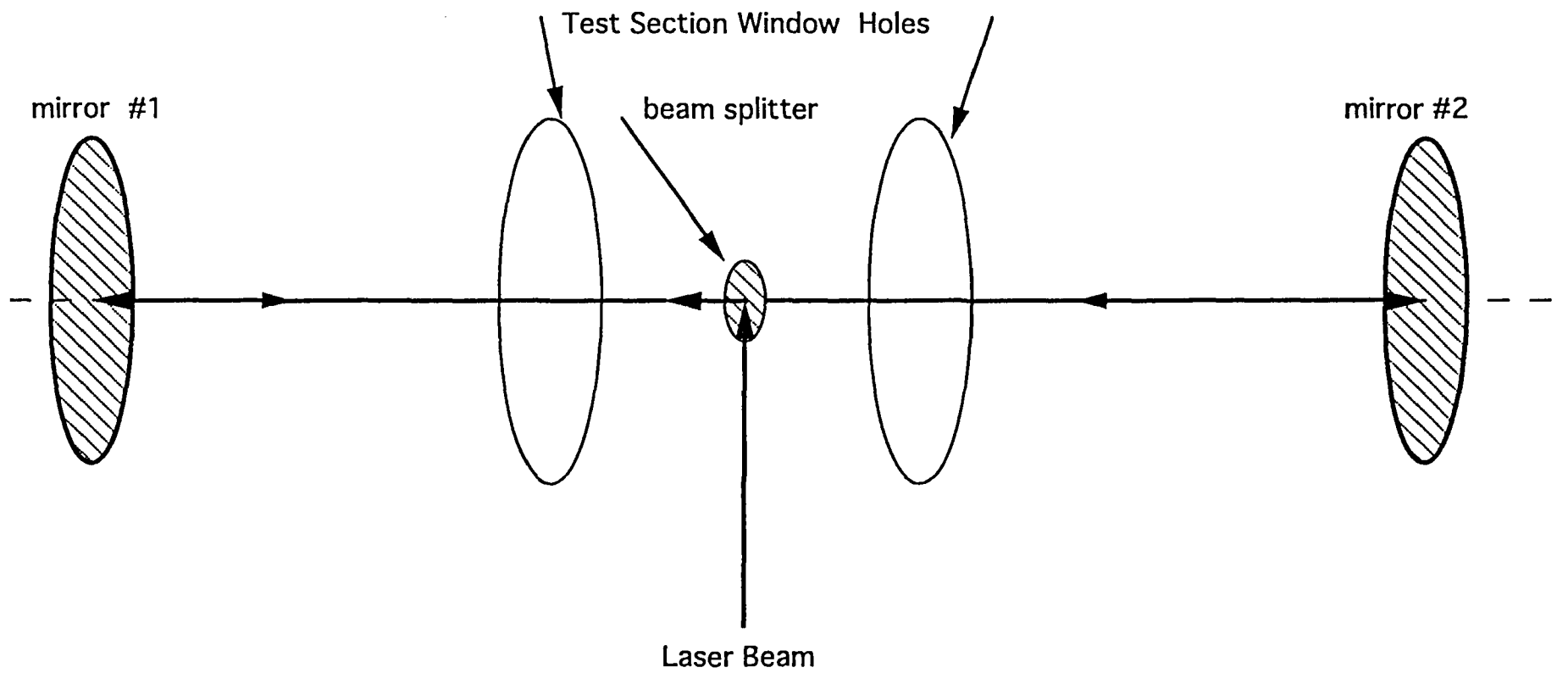


Figure 6. Auto-alignment scheme.

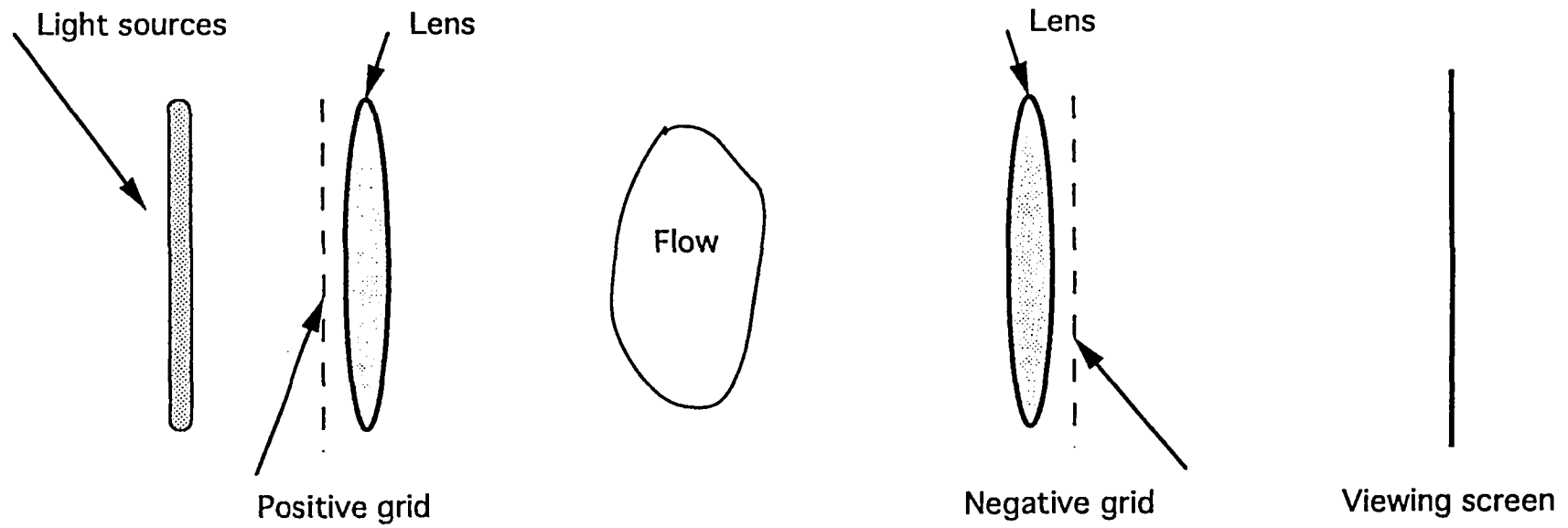


Figure 7. Focus Schlieren: Kantrowitz & Trimpi.

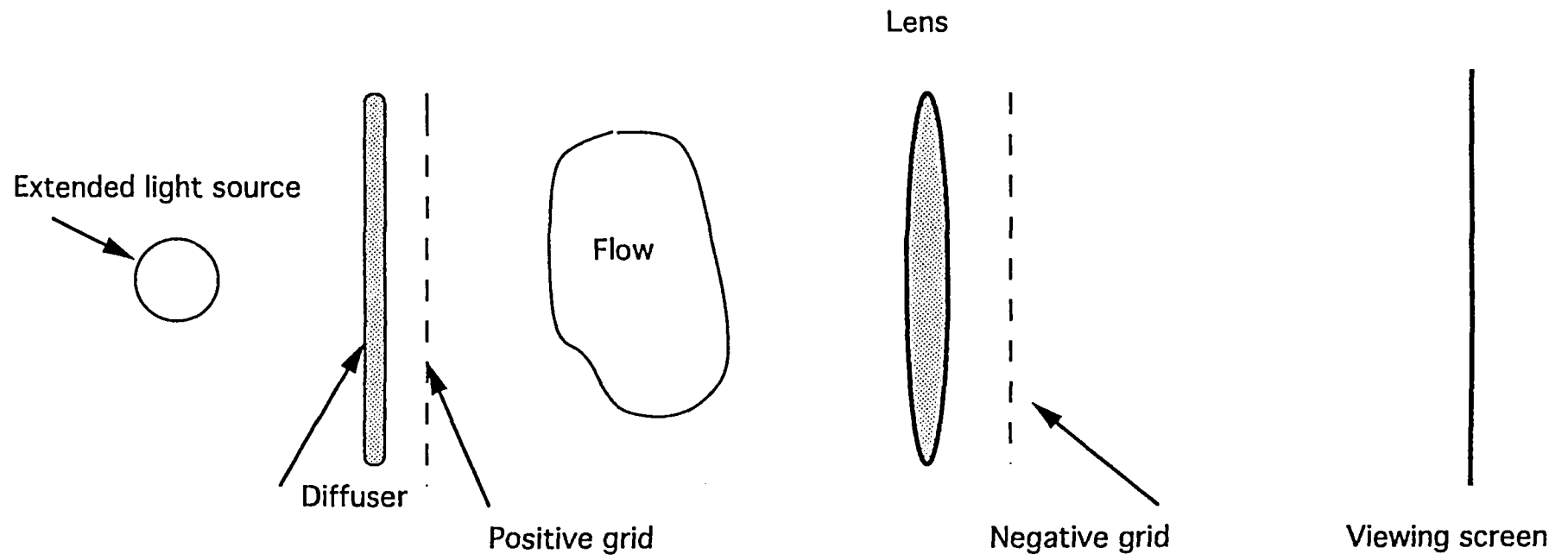


Figure 8. Focus Schlieren: Burton.

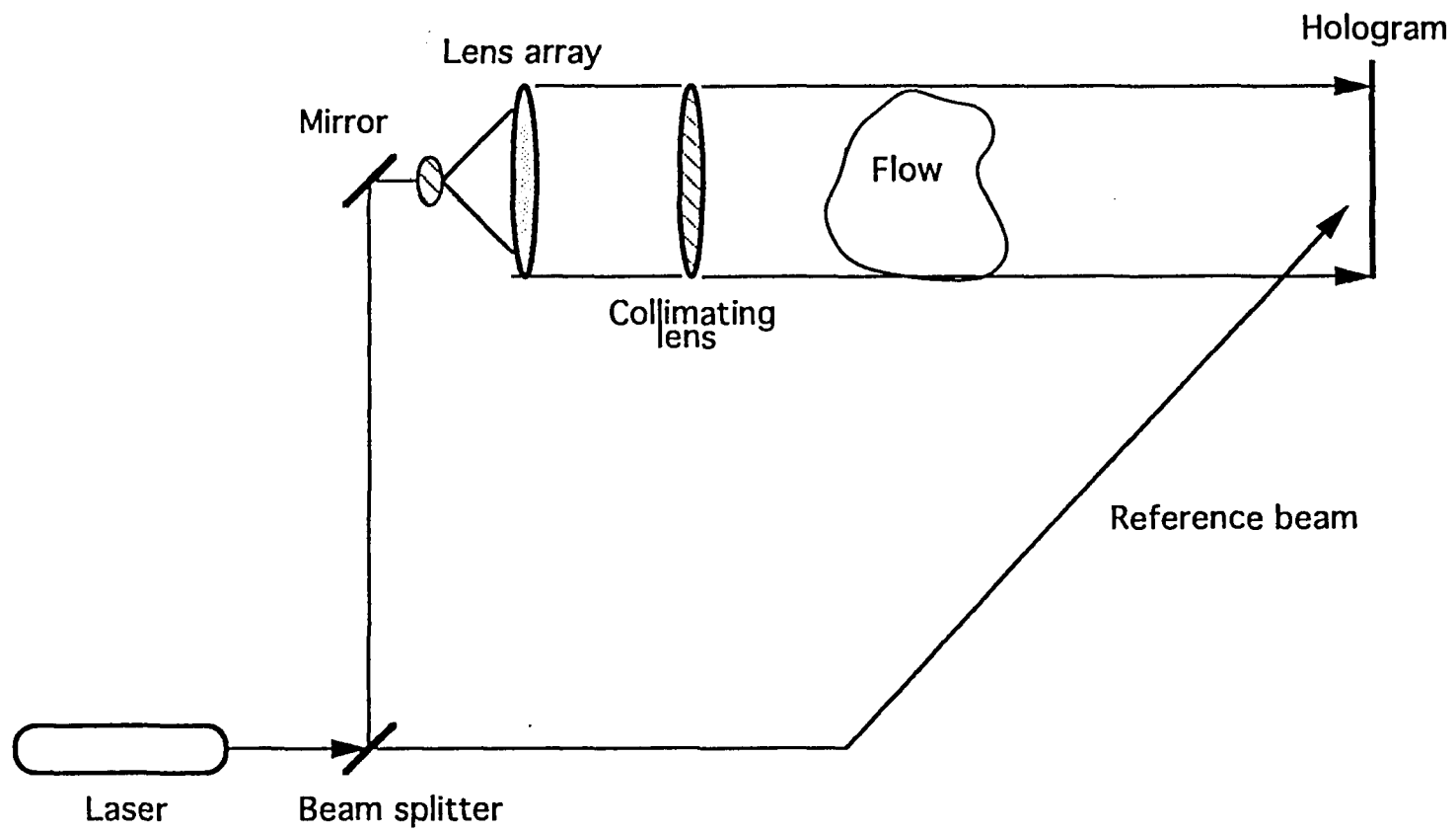


Figure 9a. Holographic Focus Schlieren—Experimental Setup.

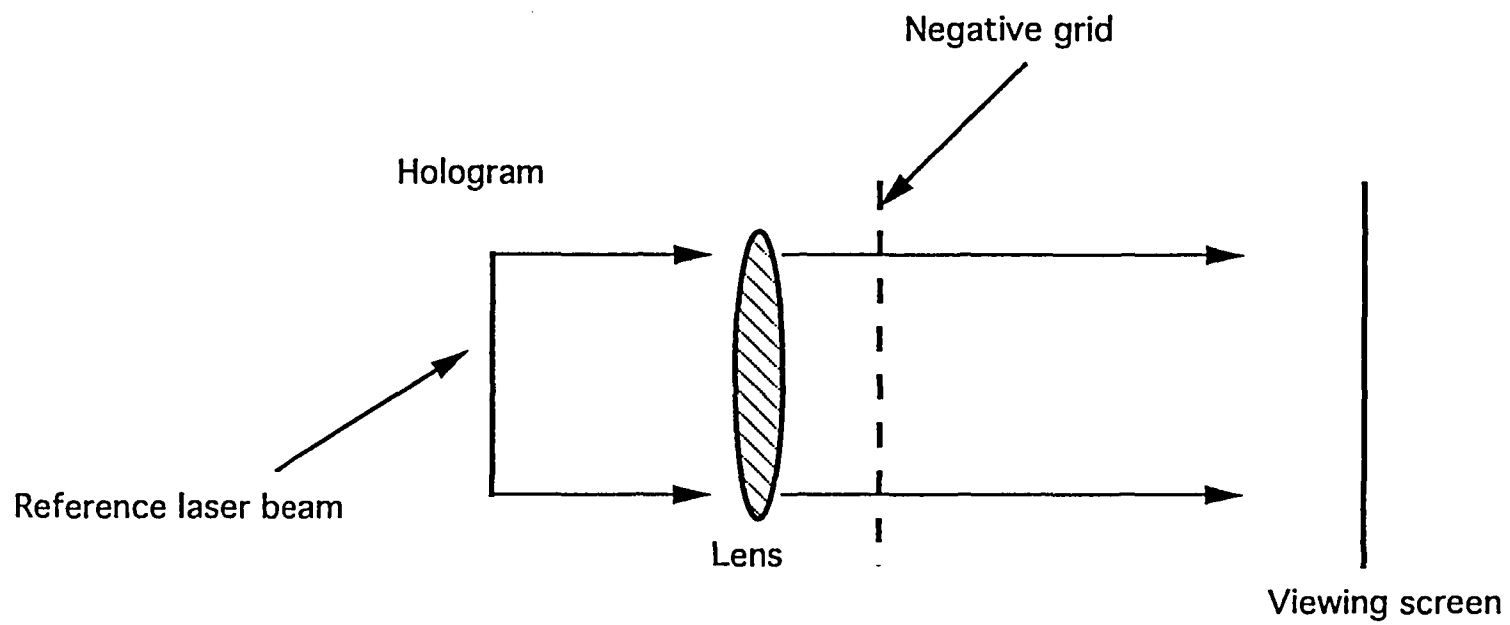


Figure 9b. Holographic Focus Schlieren—Reconstruction Setup.

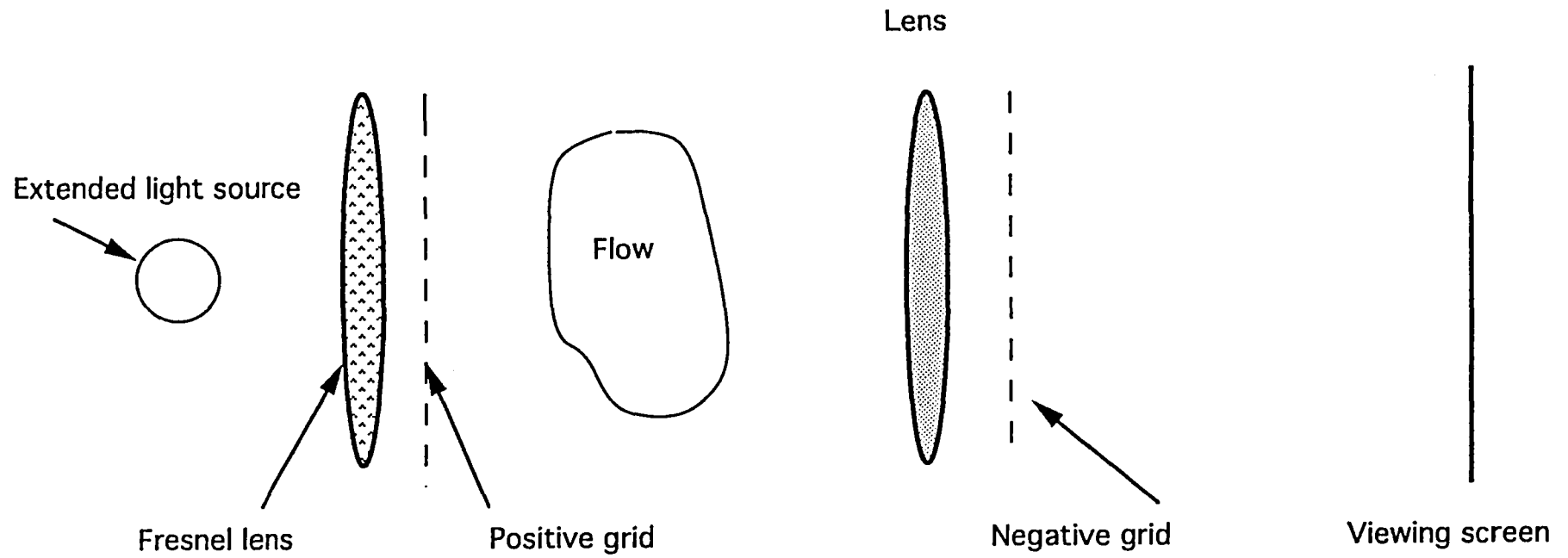


Figure 10. Focus Schlieren: Weinstein.

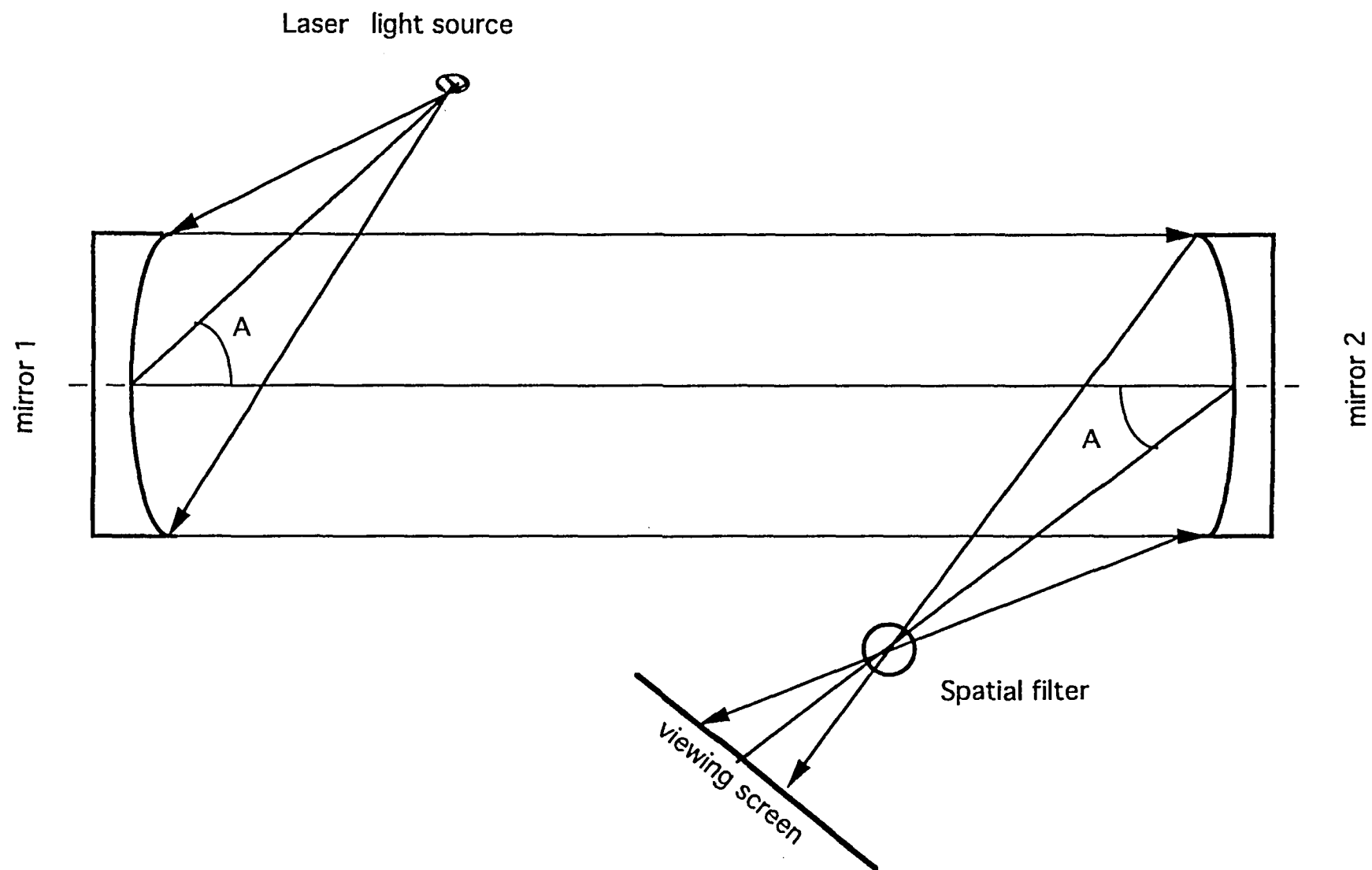


Figure 11. Schlieren Interferometer.



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